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Simulating past land use patterns; The impact of the Romans on the Lower-Rhine delta in the first century AD

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1. Introduction

By the end of the first century BC the military conquest of the Romans had brought their armies to the Lower-Rhine delta in the present-day Netherlands. In the following centuries the river Rhine became the northern *Limes* or border of the Roman Empire. To protect these borders, but also to regulate trade with the Germanic tribes to the north, the Romans established fortifications alongside the Rhine (Zandstra and Polak, 2012; Polak, 2009). The arrival of the Romans in the Lower-Rhine delta is accepted to have had a significant impact on the local inhabitants and their surrounding landscape (Willems, 1986; Bloemers, 1978; Vos, 2009; Kooistra et al., 2013; Van Lanen et al., 2015). Not only have they constructed road networks and a series of forts and watchtowers, they have also impacted the use of the land for the production of food.

Previous studies have shown that part of the food was imported and part of it was locally produced (e.g. Groot et al., 2009; Heeren, 2009; Van Es, 1981; Willems, 1986). This meant that farmers, who had until then been mainly producing for themselves, had to increase their production to generate sufficient surplus to meet the demands of the Roman army. However, relatively little is known on the extent of this local production potential and regional-scale impacts on the landscape. The scarce and isolated character of the available archaeological evidence makes it problematic to estimate the extent of local food production.

Van Dinter et al. (2014) and Kooistra et al. (2013) are the first to attempt to systematically research the land-use impact of the Roman military and *vici* inhabitants in the Lower Rhine delta. They analysed whether the local population could supply the Roman army in 70 CE and 140 CE in a diptych of articles. For this they have, through extensive calculations, estimated the required food and wood and translated these demands into hectares of land. By confronting these with available land resources for three sub-regions in the Lower Rhine delta (Fig. 1), they have reconstructed the impact of the Roman presence on the land use and concluded that the rural population and the landscape could meet the reconstructed additional demand for food.

In this article we study the impact of Romans on the land use in the Lower Rhine by exploring a spatial simulation modelling framework that integrates economic and demographic factors with physical-environmental factors to simulate past land use on a regional level. For this we have re-examined the study of Van Dinter et al. which we extended with spatial interactions and economic competition. More specifically we have looked at the regional potential for food production. The work of Van Dinter and colleagues contains many assumptions that can be debated (Groenhuijzen and Verhagen, 2017). However, the main focus of our analysis is to understand whether the proposed simulation approach can aid in a better understanding of past spatial dynamics. We re-evaluate the work of Van Dinter and colleagues by extending it with spatial interactions and economic competition. This application illustrates the potential of our modelling framework to test hypotheses related to past land use.

Van Dinter et al. assume that 50% of the cereals consumed by the Romans was locally produced and that the remaining half was imported. These shares are rough estimates that are not supported with other sources. In order to understand whether this percentage is feasible, we formulate a set of scenarios with varying percentages of assumed local cereal production. Through these scenarios we aim to generate an understanding on the maximum capabilities of the landscape and labour force to meet the demand for food. We analyse which share of the Roman food demand may have been produced locally and thus test the feasibility of the 50% proposed by Van Dinter and colleagues.

The spatial simulation modelling framework that is introduced in this article and that we refer to as the Past Land Use Scanner (PLUS), integrates economic and demographic factors with physical-environmental factors to simulate past land use on a regional level. In the modelling framework we consider regions to be coherent areas in terms of their physical landscape and culture. The size of such areas is dependent on the objectives of the study, the land land-use dynamics that are involved and the spatial range of the drivers that are assumed to influence these dynamics. In the case presented in this article we selected the final stretch of the Lower Rhine that comprised the daily living environment for the local population along the Roman Limes. The area is centred around the reconstructed limes road. Its physical

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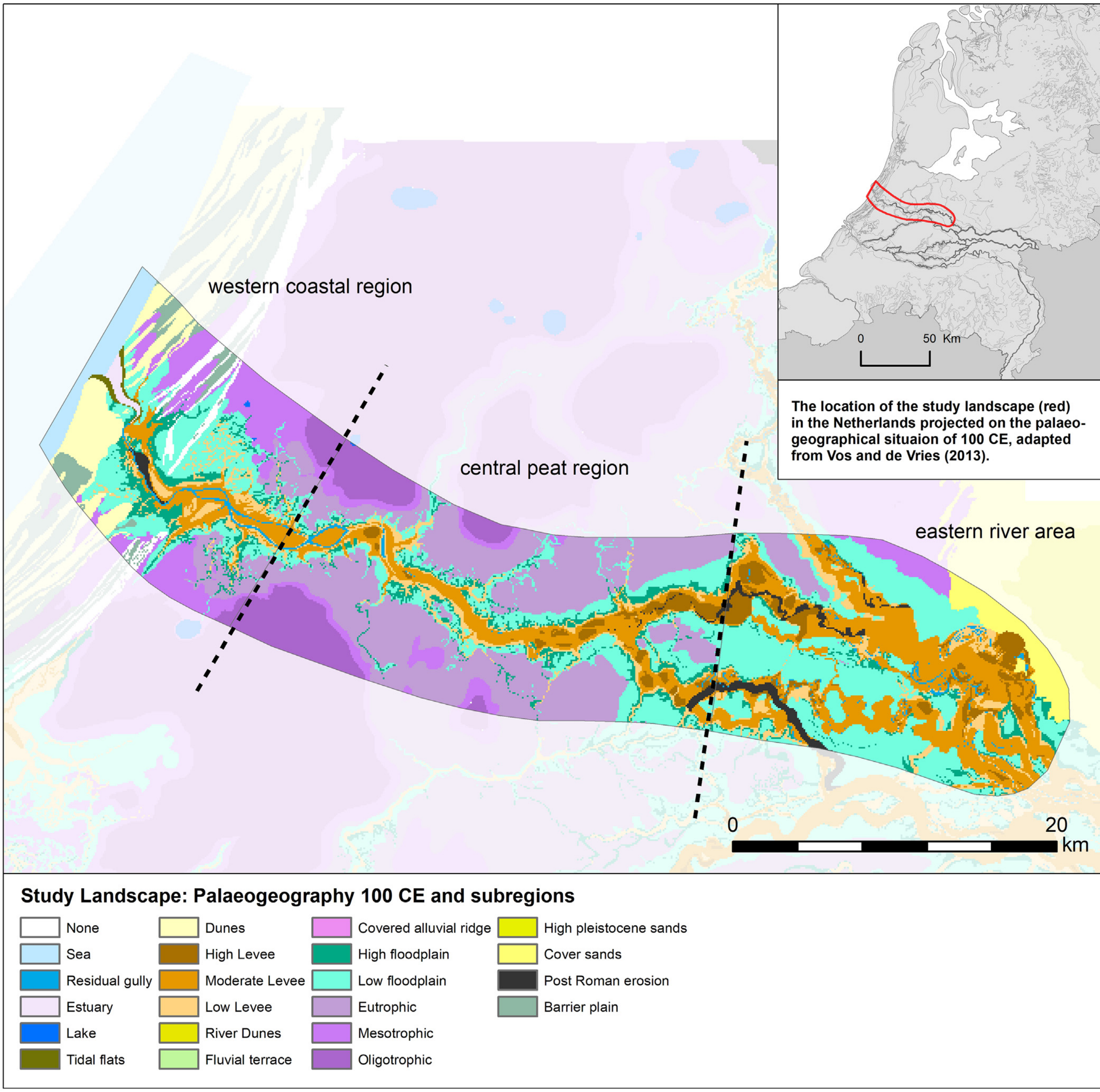

Fig. 1. Study landscape Van Dinter et al. (2014) projected on palaeogeographical reconstruction Groenhuijzen and Verhagen (2015).

landscape consists of levees, floodplains and neighbouring peatland and stretches until the dunes in west. The region's borders are defined by the North Sea in the west, the fairly inaccessible peatland to south and north and the slightly more elevated, sandy areas in the east that are characterised by a different agricultural potential and other land-use dynamics (Van Lanen et al., n.d.). Model applications may consist of multiple different regions as long as the different dynamics in the constituting regions are properly addressed.

The modelling framework has its roots in economic theory and simulates the allocation of land-use change by mimicking the competition for land among different types of use. The modelling framework has originally been developed to simulate land-use development in the near future and is known as Land Use Scanner (Hilferink and Rietveld, 1999; Koomen and Borsboom-Van Beurden, 2011). For the present study this modelling framework has been rethought and operationalized in order to simulate past land-use change. Land-use simulation is based on estimated regional demands for various land-use types combined with local assessments of suitable locations for these uses. The regional demands are based on a combination of economic and demographic scenarios. The local suitability for certain land-use types is based on distance relations, physical characteristics of the landscape, limitations resulting from military and political processes and available techniques to work the lands. To balance the demand for land of different types of use with the supply of suitable locations a logit-type approach is applied.

Within simulation models the real world is translated into a collection of variables linked by mathematical or logical conditions (Lake, 2014). As identified by Lake (2014) one of the major challenges is the integration of sociological factors. Especially on site catchment and household-level various researchers have effectively attempted to

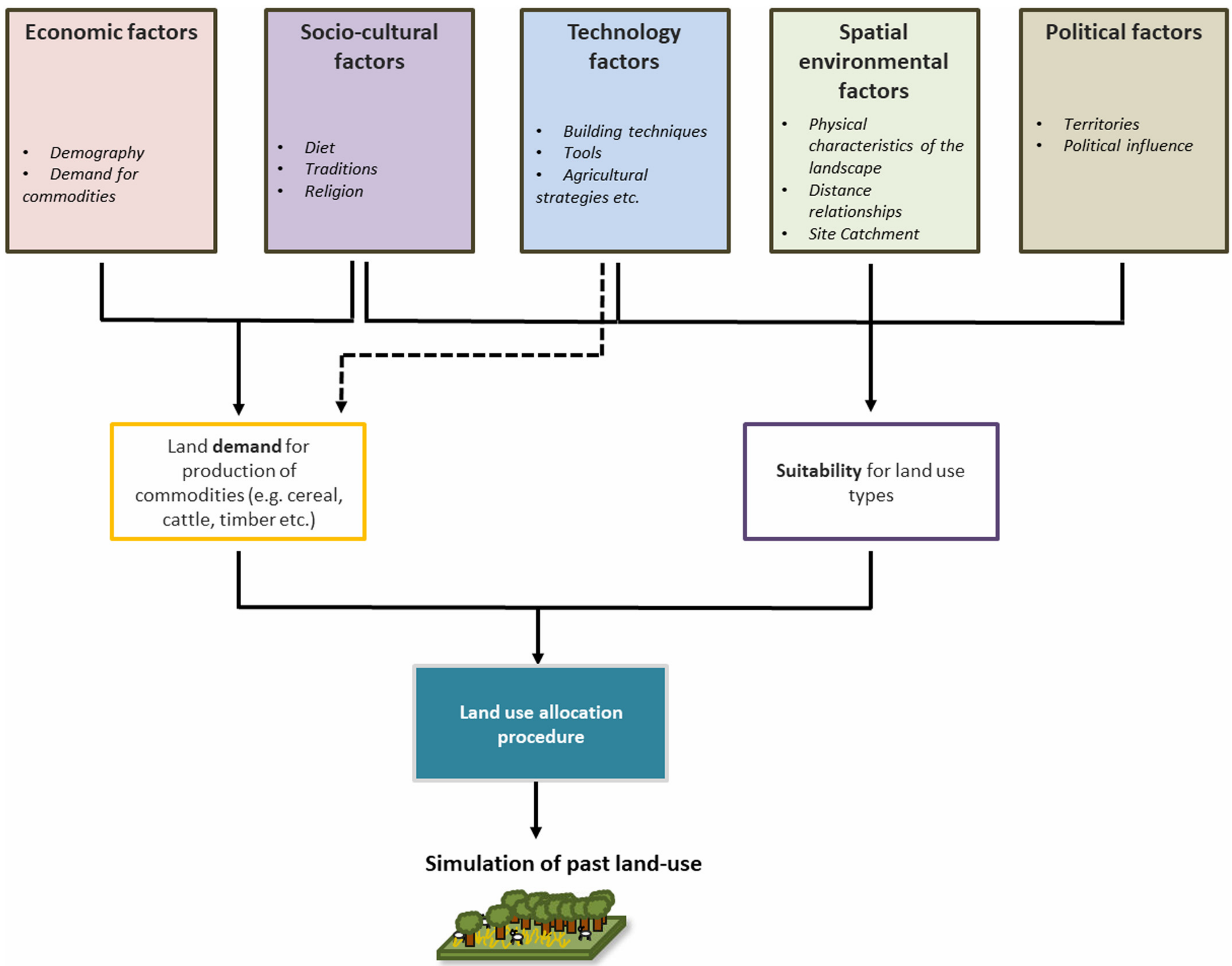

Fig. 2. Schematic overview of conceptual modelling framework (based on Bürgi et al. (2004) and Diogo et al. (2015)).

integrate complex cultural and sociological factors (e.g. Van der Leeuw and McGlade, 1997; Goodchild and Witcher, 2010; Whitley et al., 2010; Danielisová et al., 2015). Besides some remarkable examples (e.g. Kohler, 2000; Kohler and Varien, 2012), the integration of sociological factors in simulation models that perform on a larger, regional area are scarce. This article aims to contribute to this research field by presenting a model that allows integrating socio-cultural and natural factors at a regional scale. The model can be used to simulate the interrelationships between socio-cultural and bio-physical factors and test hypotheses on human interactions with the natural landscape in the past.

The article is structured as follows. First the simulation modelling framework is described in Section 2. The configuration and methodological steps to operationalise the simulation model for the Lower-Rhine delta in the first two centuries is presented in Section 3. In Section 4 the main results of the simulation model are presented, followed by a discussion in Section 5 and a concluding Section 6. Section 7 provides an outlook for future research.

2. The past land use scanner simulation framework

2.1. Conceptualizing the land-use simulation framework

At the core of the PLUS modelling framework a distinction is made between regional demand for land for different types of use and a local definition of suitability for these uses. To understand how demand and suitability are determined and translated into different scenarios, several main driving forces are distinguished. For this we propose a conceptual framework that is based on Bürgi et al. (2004) and Diogo et al. (2015) who distinguish the following interrelated components which we translated to past situations:

- **Economic factors**, provide the demand for goods (e.g. food, wood) based on estimates of the demographic characteristics of rural settlements and larger entities, such as cities or military units for which a local production surplus is required.
- **SOCIO-cultural factors**, such as diet, the organisation of settlements and land-use systems, traditions and religion that can limit or stimulate areas to be used or result in modification of a demand.
- **Technological factors**, relating to, for example, tools or strategies (e.g. crop rotation systems) that allow different types of terrain and (marginal) land to be cultivated.
- **Spatial and environmental factors** that we separate into spatial relationships between entities in the region (e.g. site catchment parameters as described by Higgs and Vita-Finzi (1972) and travel time through the landscape such as proposed by Groenhuijzen and Verhagen (2015) and physical environment factors such as soil type and geomorphology.

- **Political factors**, for example territorial restrictions and trade agreements.

While regional land demand is expected to be mainly dependent on economic and socio-cultural factors, local suitability is assumed to be mostly influenced by technological, spatial, environmental and political factors. An important aspect in defining local suitability is the balancing of those factors. To determine which factors are more influential, a relative weighing of the different data layers describing these factors is necessary. There are several examples in which such weighing methods in the archaeological domain has been applied (Verhagen et al., 1999; Robb and Van Hove, 2003; Kohler et al., 2007; Whitley et al., 2010; De De Cet et al., 2015).

The model can integrate socio-cultural factors that influence land-use patterns by integrating thematic layers related to the assumed suitability of locations. For past situations, spatially explicit information is often lacking on the spatial implications of beliefs, customs and traditions that may have limited local people in the use of their landscape (Lake, 2014). This void may partially be filled by integrating outcomes of small-scale simulation studies and translating these into multiple, regional-level scenarios. Considering the cultural factors included in the case study we have integrated information on settlement size and density – being relatively homogeneous with an average size of 1.5 households – and the assumed diets – mostly cereal and meat – for the local population and Roman military (see Section 3.2 and Bloemers, 1978; Willems, 1986; Vos, 2009; Heeren, 2009). These preferences result from the customs and traditions of the region's inhabitants during the studied period and can differ when applying the modelling framework to a different study landscape and period.

The combination of local suitability and regional demand form the input for the allocation procedure which is based on Mc Fadden's discrete choice theory (see Fig. 2 for a schematic overview). The probability that an actor chooses a certain alternative is dependent on the utility of that specific alternative in relation to the total utility of all alternatives (Mc Fadden, 1978). Translating this into land use, the model bases the probability of occurrence for a certain land-use type at a location on the suitability of that location for that type of use in relation to the total suitability of all possible uses at that location (Hilferink and Rietveld, 1999). Recent validation efforts have indicated that current, observed land-use patterns can be reproduced by this modelling approach if sufficient information on regional demand and local suitability is available (Loonen and Koomen, 2009; Koomen et al., 2015; Diogo et al., 2015).

2.2. Operationalizing the simulation framework

To operationalize the PLUS the software GeoDMS has been used (www.objectvision.nl/geodms). This specialized free and open source GIS modelling software is highly efficient for raster based calculations and allows for the efficient and fast simulation of multiple scenarios at a high resolution (Lavalle et al., 2011).

The allocation process of the various land-use types is operationalized using the following formulation (see Koomen et al., 2011):

$$M_{cj} = a_j \times b_c \times e^{Scj}$$

where:

M_{cj} is the amount of land in cell c expected to be used for land-use type *j*;

a_j is the demand balancing factor that ensures that the total amount of allocated land for land-use type j equals the specific demand;

b_c is the supply balancing factor that ensures that the total amount of allocated land in cell c does not exceed the amount of land that is available for that particular cell;

e^{Scj} is the suitability of cell c for land-use type j based on its physical properties and neighbourhood relations of which the importance of the suitability value can be set by adjusting a scaling parameter.

The values of a_j are determined in an iterative approach that simulates a competitive bidding process between different types of users for their preferred type of land use. Users represent homogeneous groups of individuals whose behaviour results in a specific type of land use. For example farmers who are active in arable farming. Depending on the degree of specialisation these individuals may be active in one or more types of use. The model assumes that every type of user will attempt to get their desired amount of land – the demand – allocated at their preferred locations but can be outbid by another if the relative suitability for that land-use type is higher at that specific location. Allocation follows suitability values but is constrained by overall demand, so little to no land will be allocated to fairly suitable locations if more suitable alternatives exist. Moreover, land-use types may not be allocated to their most suitable locations if these locations are more suitable for other types of use or if very few suitable alternatives exist for these other types of use.

3. Model implementation for Lower-Rhine delta

3.1. The land-use system

The PLUS framework is set up to model multiple land-use scenarios for 70 CE and 140 CE. Within PLUS we simulate three types of land use related to the production of food: arable farming, meadow and pasture (Table 1). In addition the model includes woodland, water, residential and military. Woodland is approached as a passive land-use type, allowing it to be replaced by the food producing land-use types. We refrained from simulating changes in woodland coverage as we lacked accurate data and reconstructions on the spatial distribution and composition of woodland. The other land-use types are considered to be exogenous in the model, meaning that they are approached as static elements in the simulation process.

3.2. Suitability for land

The local suitability for endogenous land-use types in PLUS is determined by physical characteristics, spatial relationships and political and military aspects. For the physical environment characteristics, the cultivation options per land-use type depend on the available technologies and land-use management strategies combined with the physical characteristics of the landscape. For the physical landscape the palaeo geographical reconstruction for 100 CE, developed by Groenhuijzen and Verhagen, 2015 based on Cohen et al. (2009), Vos and De Vries (2013), Van Dinter et al. (2014) is used. This reconstruction is valid for both 70 CE and 140 CE. To determine the suitability of the various palaeo geographical units for different types of land use we apply a relative scoring method developed in collaboration with Marjolein Gouw-Bouman (palaeo-ecologist, Utrecht University) that quantifies the land-use potential of different palaeogeographical units. Every landscape unit received a suitability score on a 0–5 scale with 0 representing unsuitable and 5 representing very suitable (see Appendix A).

A second aspect in the definition of local suitability is the inclusion

Table 1
Endogenous land-use types in Lower Rhine region in Roman period (adapted from Van Dinter et al. (2014) and Kooistra et al. (2013).

Land-use type	Description
Arable farming	This land-use type produces crops and cereals for food.
Pasture	Pasture is used as grazing land for cattle to produce food (foremost meat and meat products).
Meadow	Meadows are used to harvest hay as food for cattle during winter.

of spatial relationships. We apply site catchment theory (Higgs and Vita-Finzi, 1972) to obtain the area people could reach within one hour walking time from a settlement. The friction model of Groenhuijzen and Verhagen (2015) was applied to incorporate the effect of physical characteristics of the landscape on walking speed. In line with the seminal work of Von Thünen (1842) on the pre-industrial spatial configuration of agricultural areas we assumed the efforts related to travelling to the fields and transporting produce to influence local suitability for the different types of agricultural land use. Arable farming requires most effort in care for crops, harvesting and transporting the raw products to the markets and is thus assumed to be located closest to the settlements followed by pasture and meadows (Hughes et al., 2018).

The different components comprising suitability are added up after applying weights reflecting their assumed importance. This deductive approach was informed by relative scores that are presented in Appendix A. For instance, for arable farming we expect the distance to settlements to be more important than physical suitability. Based on site catchment theory we assume that people would not have been willing to walk more than 1 h to their lands and would at least have a certain minimum suitable land around their settlement. We have therefore configured the relative attractiveness of arable farming within half an hour walking distance and 1 h walking distance to be higher than the physical suitability. To avoid unsuitable areas near to settlement to be used for arable farming, we have included the condition that excludes all locations with a physical suitability score of 0. The final suitability for the various land-use types is thus a weighted sum of all suitability factors reflecting an integration of the knowledge on the different forces that drive land-use choices that is available among different groups of experts (i.e. Groenhuijzen and Verhagen for distance relations and Marjolein Gouw-Bouman for the physical suitability) Appendix A describes the exact suitability definitions for the different types of land use.

3.3. Demand for land and required labour force

To study the impact of different assumptions on the share of food that could be produced locally we formulated several scenarios and applied our modelling framework to simulate the corresponding landscape. By doing so, we test the validity of their hypothesis and explore the limits of the landscape to produce the required amounts of food. In addition, we check whether this amount of food can be produced by the workforce available in the settlements.

For each time slice we defined eleven scenarios in which we vary the amount of the local food surplus as share of the total amount of required food in the region in steps of 10 from 0 to 100%. To estimate the total land area needed to produce these amounts of food per sub region (i.e. western coastal region, central peat area and eastern river area) we have used an updated archaeological dataset in which locations of known archaeological sites and find spots from the Archaeological Information System of the Netherlands (Roorda and Wiemer, 1992; Wiemer, 2002) have been reassessed to minimises errors related to, for example, the representation of single sites as multiple points. This reassessment was done by Verhagen, Joyce and Groenhuijzen in the context of Finding the limits of the Limes project (https://limeslimits.wordpress.com/). For the demand for food we have looked at the size of the different settlements in the area. Previous studies suggest that rural settlements for this period in this region are relatively homogeneous. An average settlement is estimated to consist of 1.5 households of about 5 to 8 persons (Bloemers, 1978; Willems, 1986; Vos, 2009; Heeren, 2009). So we estimate the average settlement size to be around 10 persons per settlement. Based on these estimates we calculated a food demand and required land area following the assumptions related to calorie per food type and local agricultural production potential per hectare described Van Dinter et al. (2014). Detailed calculations are provided in Appendix B.

Rural settlements managed 12.8 ha of arable farming on average (see Van Dinter et al., 2014, p50). Assuming that a two-field rotation system in which half of the land would be fallow was applied, this equals a maximum area of 25.6 ha for each settlement (see Table 2 for the calculated labour force per region and time slice). Additionally, for 140 CE the sub regions have been split in a northern and southern part, following the hypothesis that the Roman army and vici only obtained their resources south of the border (Kooistra 2009; Van Dinter et al., 2014).

Table 2
Maximum capacity of arable land that the labour force from the rural settlements can handle.

	70 CE			140 CE		
Region	Western coastal region	Central peat region	Eastern river region	Western coastal region	Central peat region	Eastern river region
Number of rural settlements	39	9	115	48	16	132
Maximum capacity of arable land for settlements (ha)	998	230	2944	1229	410	3379

4. Results

Fig. 3 shows the predominant land-use types for the different food producing lands for 70 CE and 140 CE for 0%, 30%, 50%, 70% and 100% local cereal surplus for the Roman military and vici inhabitants. In addition to the spatial representations we have performed an overlay analysis which allowed us to understand on which palaeogeographical unit the different food producing lands have been allocated. Fig. 4 shows the results of this overlay analysis which includes the total land demand and the capacity of the labour force. Looking at these results the following observation on the simulation modelling outcome can be made (see Appendix C for all the raw results, modelling software and configuration).

4.1. Arable farming

Except for the eastern river area, the demand for arable farming can in every scenario be met for 70 CE. For the eastern river area the demand can almost be met. This indicates that the pressure for land is already very high for that region in that period. For 140 CE the demand for arable farming can in most scenarios not be realised. The simulation outcomes show that even at low percentages of local surplus production the land is the limiting factor to supply sufficient surplus.

Looking at the variation of the allocated uses of land by confronting it with the palaeogeographical unit it is simulated on it can be observed that for the western coastal region arable farming is placed in less suitable dune areas to fulfil the demand for food. This result suggests that we should carefully reassess archaeological and palaeo-vegetation studies for these areas or reconsider the assumptions in relation to the share of locally produced food. For the other regions arable land is most commonly allocated on the moderate levees, followed by the high and low levees.

Considering the labour force we can observe that for the western coastal region and eastern river area this is not a limiting factor. For the central peat area, the labour force seems to be a limiting factor after 30% of local surplus production. This accounts both for 70 CE and 140 CE.

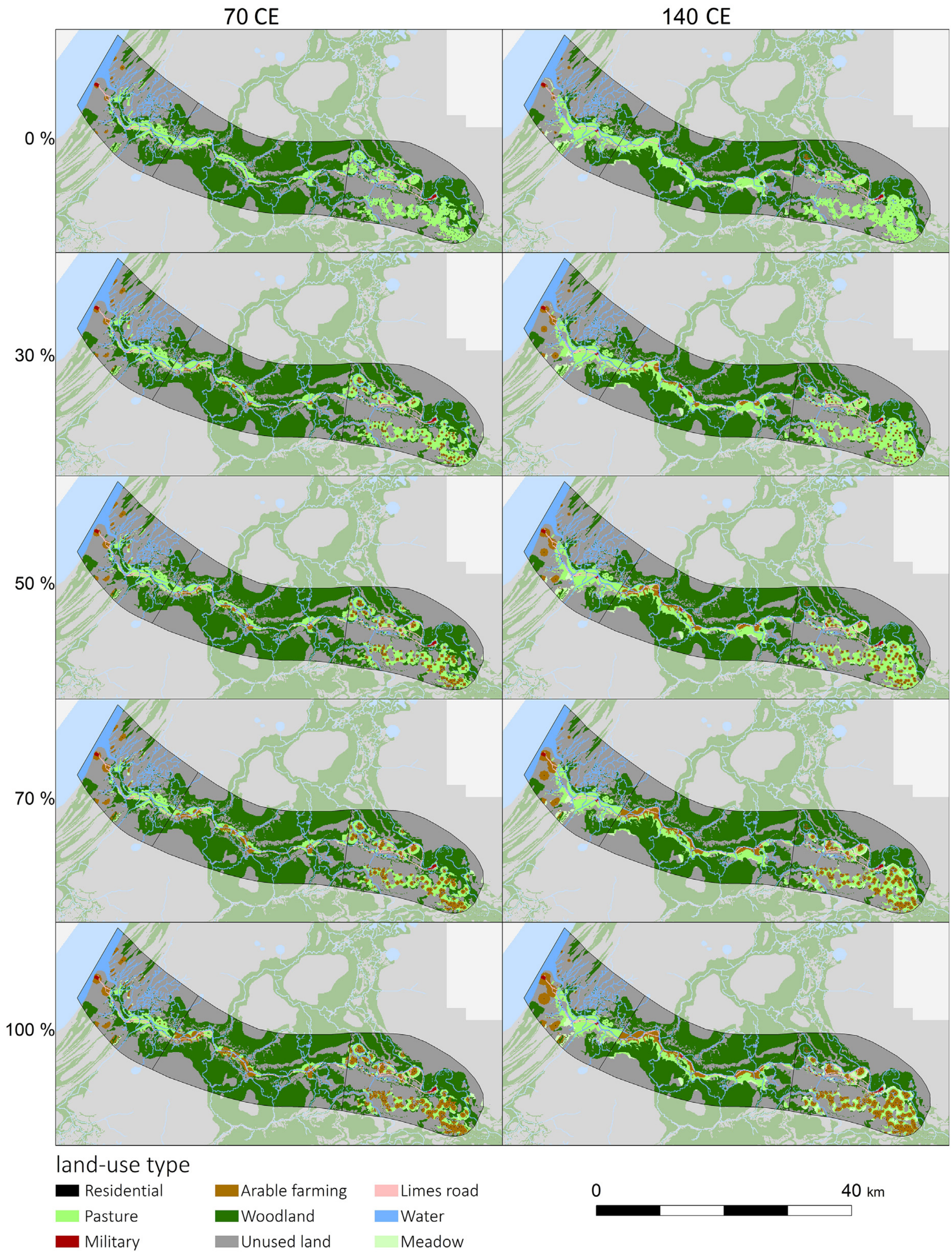

Fig. 3. Predominant land-use types for different scenarios for local production of cereal surplus for the Roman military and vici inhabitants for 70 CE and 140 CE.

4.2. Pasture

For pasture a similar trend is noted as for arable farming when comparing 70 CE and 140 CE. For 70 CE the demand can be met for almost every scenario, but for 140 CE it cannot. The amount of pasture land decreases when the share of food surplus production increases. This is the consequence of the fact that we assume a two-field rotation system for arable farming. Since fallow arable farming is assumed to be used as pasture as well, the areas for pasture do not decrease but are “hidden” under arable farmlands.

The variation in landscapes where pasture is observed indicates that an increasing demand for arable farming forces pasture to less suitable areas, such as high floodplains. This is especially visible in the western coastal region. For the central peat region at around 50% surplus

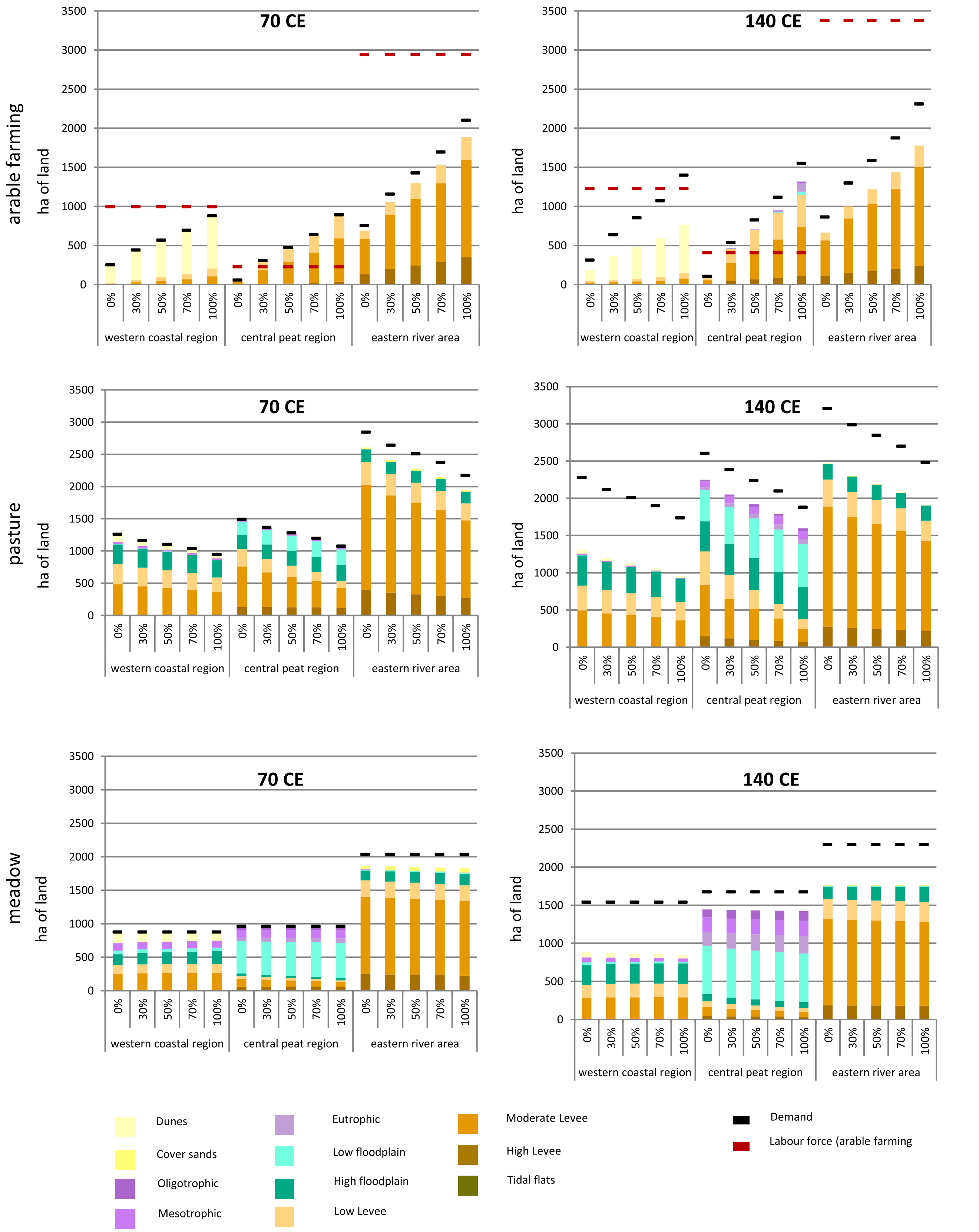

Fig. 4. Realisation of land use according to different local production scenarios (in percentages) for 70 CE and 140 CE for the different sub regions.

production in 70 CE, pasture is more found on floodplains than on the lower levees. In 140 CE the allocation of pasture on levees decreases drastically in favour of low and high floodplains. This strong competition for land on the levees is not visible in the eastern river region. Here, pasture is found most commonly on the moderate levees, followed by the high and low levees.

4.3. Meadow

In the 70 CE scenarios it is also possible to find enough suitable land for meadows. For 140 CE the pressure for land is too high and the simulation is not able to allocate all required meadow land. Concentrating on the spatial variation of meadows we observe that for 70 CE meadows in the central peat area are pushed to the less suitable low floodplains. In 140 CE a shift can be noted in the western coastal area. At 10% cereal surplus production high floodplains, moderate levees and mesotrophic peat areas are the most cultivated palaeogeographical units on which meadow appears. Increasing the demand for 140 CE forces meadows even further into eutrophic and mesotrophic peat areas.

5. Discussion

Based on the results of the presented case we conclude that the hypothesis of Van Dinter et al. (2014) that 50% of the cereal for the Roman military and vici inhabitants was produced locally seems to hold for 70 CE. For 140 CE it appears that their hypothesis does not. For this period the results point towards rejecting and re-evaluating the hypothesis of Van Dinter and colleagues.

Considering the availability of suitable land for 70 CE a local production would have been possible in the western coastal area and central peat area even when a much higher demand would be required. For the eastern river area in 70 CE there seems to be sufficient land, however it must be noted that it is pushed to its limits. For 140 CE it is clear that the region does not contain sufficient useful land to meet the demand for the various food producing land-use types. The results show that the area does not have sufficient suitable space for the food producing land-use types. There is not enough suitable land to meet the demand in almost every scenario.

For both 70 CE and 140 CE the labour force does not seem to be the limiting factor except in the central peat area. However, it must be noted that the adjacent regions appear to have had enough labour force available, making it possible that people from that region might have helped other regions on labour intensive periods.

Besides improving the understanding whether or not the landscape could provide enough suitable food producing lands and if the settlements have sufficient people to work the lands, this study also show patterns in land-use. This allows the exploration of the spatial distribution of various land-use types over different landscape types and palaeogeographical units. The simulation thus reveals possible land-use patterns that can indicate areas with potential archaeological value that have hitherto been under explored. For arable farming in the western coastal areas it can be noted that it is mostly allocated on dune areas knowing that these soils are less fertile compared to other palaeogeographical units (see Appendix A). It is therefore fair to assume that people were also relying on other food producing activities like fishing; however exact figures on the amount of food this would produce are difficult to reconstruct. For meadow and pasture in the central peat area it can be noted that the model simulates significant parts to the less suitable low floodplains and mesotrophic peat areas. Identifying this could lead to reformulate the hypothesis of pasture and meadow in the area. The results could indicate for alternative economic activities or specialisation.

Inherent to any spatial modelling approach the PLUS simplifies reality. In case of arable farming, for example, the modelling framework is configured to simulate this land-use type to an area within 1 h walking distance from a settlement. This rule has a significant impact on the results. It might have been that people were willing to travel longer to their lands or that arable farming was more systematically organized. Here the results thus provide interesting leads to formulate hypotheses considering the land organisation. Furthermore this study has not differentiated different types of settlements. The analysis could greatly benefit from having more detailed data on estimated sizes of individual settlements to provide more variation in associated land-use patterns and available workforce.

Another aspect is that the settlements integrated in the model are all known sites from archaeological research activities (i.e. excavations, surveys and historical sources). Obviously not all settlements are found or archaeologically traceable. Bult (1983) and Deeben et al. (2006) for instance estimate that 50% of the sites have not yet been found. For the central peat area in 70 CE this could mean that the labour force was not the limiting factor to produce sufficient food. For the eastern river area many more settlements would have an even more dramatic effect on the available land, which is already relatively scarce. In addition to these limitations, our simulation is likely to suffer from edge effects. Settlements near the borders of the sub-regions may have suitable land available in neighbouring sub-regions that is currently not considered because the demand for land is confined within the boundaries of sub-regions. Technically it is possibly to relax this constraint, but this has not yet been implemented in the model.

As with all simulation modelling the input parameters determine the results. In the presented case we relied heavily on the study of Van Dinter and colleagues. Some of their assumptions can be questioned. They suggest, for instance, that an average settlement requires 12.7 ha of pasture to feed their cattle herds, assuming a density of 3 bovines per hectare (see Appendix B). Other researchers, however, have proposed much lower densities for comparable landscapes. Baum (2016) states that the amount of required land is also dependent on the quality of the land and suggests that one cow would require at least 1.2 ha and possibly a bit more. Using these values would have resulted in a much higher demand for pasture. In that case we would have seen that the allocation of pasture and meadow to less suitable land – i.e. peaty areas – would have already occurred with relatively low amounts of local cereal production. Such outcomes can inspire new research ideas and suggest new locations for archaeological fieldwork. The PLUS framework can thus be used to test existing hypothesis and develop new ideas on how past civilsations interacted with their natural environment.

6. Conclusions

The research presented in this article provides new insights in the land-use dynamics in the Lower Rhine area during the Roman period. The PLUS framework can be used as a research instrument to test hypotheses and inform directions of further research. Its major strength is that it integrates knowledge from multiple research fields and makes the consequences of the different assumptions spatially explicit. For the case study, especially the land-use patterns that it produced in the west – where dunes seems to be fully cultivated for arable farming and the central peat area where pasture must have been on peaty soils – offer interesting insights that inform hypotheses for the use of the land. In addition the site catchment constraint of 1 h walking distance to arable farming can be reconsidered and extended to for instance 1.5 h walking distance. This would, for instance, imply a more organized land system and cooperation, thus offering a ground for formulating different hypotheses considering land organisation.

In order to deal with uncertainties, the modelling framework has worked with a range of scenarios. The scenarios in this article have foremost been focussed at the spatial implications of local cereal production, but the model could also be implemented to test different hypotheses and validate the associated assumptions. In the presented case economic aspects and to a limited extent sociological and cultural factors have been integrated with physical environmental factors. The PLUS is capable of integrating more sociological and cultural factors, as long as these relate to the demand for land or the spatial preferences for performing land-use related activities. The PLUS can thus contribute to the challenge identified by Lake (2014) to integrate sociological factors in simulation models. The modelling approach and tools form a dynamic research instrument that can be used for other regions and cases as well. As demonstrated in this article, the modelling framework aids archaeologists to generate a better understanding of past spatial dynamics and the relationship between the people and the landscape.

7. Future research

As a way forward we have identified various opportunities with which the research could be extended and which would improve the modelling framework. First, the modelling framework would benefit from regional vegetation reconstructions to validate the simulation outcomes. In addition vegetation reconstructions would allow narrowing down the range of scenarios and would allow simulating closer to the historical reality. Second, in order to improve the empirical basis of the various suitability components used in the modelling framework, more archaeological fieldwork would be required producing a more complete archaeological datasets. When more archaeological evidence on (Roman-era) land-use patterns and underlying decision-making processes becomes available other, statistics or utility-based quantitative weighing methods (as applied in contemporary land-use models by, for example, Koomen et al., 2015) would be considered to define local suitability. In line with that the PLUS can considerably be improved by including settlement differentiation. This would allow providing an even more precise simulation of the historical reality and would allow testing hypotheses considering specialisation and size. Another aspect for which we believe the PLUS would be a suitable research instrument is to integrate different scenarios to simulate the use of woodlands. For the specific case presented in this article Van Dinter and colleagues did produce estimates on the demand of timber for construction and timber as fuel. These figures can be translated into a demand in hectares, which could be used as input for the PLUS. However, since little data is available of the composition of woodlands which are necessary since not every tree can for be used for construction purposes and since relatively little is known on possible different wood management strategies we refrained from integrating woodland scenarios in this study. It does however provide an interesting opportunity for follow up research to test hypotheses on wood import proposed by for instance Van Lanen et al. (2016). Finally, we see a clear opportunity to test multiple views on the drivers that steer land-use dynamics (e.g. hypotheses on the demand for pasture or different diets) and to integrate the model with local-scale studies that use Agent Based Modelling (ABM) techniques (e.g. Joyce and Verhagen, 2016). It would be interesting to combine these with models like the PLUS that perform on a more regional scale. Research results from ABM on a local scale could be translated into regional scenarios. The PLUS can validate ABM modelling findings and ABM studies have the potential to inform the PLUS of the spatial preferences of the actors that steer landscape change.

Appendix A. Suitability for land-use types

Table A1
Physical suitability for arable farming.

Palaeogeographical unit	Physical suitability agriculture	Reasoning and source
Sea	na	Classified as water, exogenous
Residual gully	na	Classified as water, exogenous
Estuary	na	Classified as water, exogenous
Lake	na	Classified as water, exogenous
Tidal flats	0	High flood risk, makes it unsuitable for agriculture
Dune	3	Dunes are suitable for agriculture, however the soils are less fertile compared to other palaeogeographical units (see Van Dinter et al., 2014). This palaeogeographical unit has therefore been scored with a 3.
High levee	5	High Levees are considered to be very suitable for agriculture (Van Dinter et al. (2014))
Moderate levee	3	Based on expert judgement of Gouw-Bouman, supported by Brinkkemper (1991): various cereal types suitable to be grown on moderate levees.
Low levee	1	Based on expert judgement of Gouw-Bouman, supported by Brinkkemper (1991): a few cereal types suitable to be grown on low levees.
River dunes	3	River dunes are considered to be suitable for agriculture, however since the soils are less fertile compared to other palaeogeographical units (see Van Dinter et al., 2014). This palaeogeographical unit has therefore been scored with a 3.
Fluvial terrace	5	Based on expert judgement of Gouw-Bouman, fluvial terraces are very suitable (5) for agriculture. This palaeogeographical entity is however not present in the study area.
Covered alluvial ridge	4	Based on expert judgement of Gouw-Bouman, covered alluvial ridges are considered to be suitable for agriculture.
High floodplain	0	High flood risk, makes it unsuitable for agriculture
Low floodplain	0	High flood risk, makes it unsuitable for agriculture
Eutrophic peat	0	For this period, peat areas are not suitable for agriculture.
Mesotrophic peat	0	For this period, peat areas are not suitable for agriculture.
Oligotrophic peat	0	For this period, peat areas are not suitable for agriculture.
High pleistocene sands	4	Based on expert judgement of Gouw-Bouman, high pleistocene sands are suitable (4) for agriculture. This palaeogeographical entity is however not present in the study area.
Cover sand	4	Based on expert judgement of Gouw-Bouman, cover sands are suitable (4) for agriculture. A distinction could have been made between cover sands with a low nutrient level and a high nutrient level, however, since this is very difficult to distinguish in a palaeogeographical reconstruction, we have given it a give an average score. Since the rich areas are believed to have been more present the score was set to 4.
Post-Roman erosion	0	Post-Roman erosion processes made it impossible to provide a palaeogeographical reconstruction. We have therefore set this palaeogeographical unit to 0 excluding it from the analysis.

Table A2
Physical suitability for pasture and meadow.

Palaeogeographical unit	Physical suitability pasture (meadow/pasture)	Reasoning and source
Sea	0	Classified as water, exogenous
Residual gully	0	Classified as water, exogenous
Estuary	0	Classified as water, exogenous
Lake	0	Classified as water, exogenous
Tidal flats	3	Van Dinter et al. (2014) state that tidal flats would to some extent have been suitable for pasture. Their statement is supported by Brinkkemper (1991).
Dune	4	Dunes are considered to be suitable for pasture, however since the soil of this palaeogeographical entity is considered to have a relative low nutrient level it has not been scored as very suitable but a little less (Van Dinter et al., 2013 and expert judgement Gouw-Bouman).
High levee	5	High levees are very suitable for pasture (Van Dinter et al., 2014)
Moderate levee	5	Moderate levees are very suitable for pasture (Van Dinter et al., 2014)
Low levee	5	Moderate levees are very suitable for pasture (Van Dinter et al., 2014)
River dunes	5	Based on the soil this palaeogeographical entity is considered to be rich in nutrients making it very suitable for pasture (expert judgement Gouw-Bouman).
Fluvial terrace	5	Based on the soil this palaeogeographical entity is considered to be rich in nutrients making it very suitable for pasture (expert judgement Gouw-Bouman).
Covered alluvial ridge	5	Covered alluvial ridges are very suitable for pasture (Van Dinter et al., 2014)
High floodplain	5	High floodplains are very suitable for pasture (Van Dinter et al., 2014)
Low floodplain	2	Low floodplains are only limited suitable. (Van Dinter et al., 2014)
Eutrophic peat	0	Eutrophic peat is not suitable for pasture (Van Dinter et al., 2014)
Mesotrophic peat	0/3	Mesotropic peat is only suitable as grassland (Van Dinter et al., 2014: 10)
Oligotrophic peat	1/0	Oligotrophic peat is only suitable as hay land and bordering floodplain (Van Dinter et al., 2014)
High pleistocene sands	5	The soil map shows that high pleistocene sands are relatively nutrient, this nutrient level makes these relatively high suitable for pasture.
Cover sand	5	Cover sands - sandy aeolian deposits form the last Ice age - are considered as very suitable for pasture
Post-Roman erosion	0	Post-Roman erosion processes made it impossible to provide a palaeogeographical reconstruction. We have therefore set this palaeogeographical unit to 0 excluding it from the analysis.

Table A3
Relative demand factors for land-use types.

Land-use type	Start situation		Physical suitability		Distance relationships	
	Description	Values	Description	Values	Description	Values
Residential	Exogenous	–	–	–	–	–
Military	Exogenous	–	–	–	–	–
Water	Exogenous	–	–	–	–	–
Arable farming	For 70 CE and 140 CE this land-use type is assumed to be likely to have continued on the same locations. For 70 CE and 140 CE the output from the previous time slice has been reused and given a value of 20.	20	A score between 0 and 5 representing the physical suitability ×2	0–10	A gradual scale of 1 h walking from residential cells	0–10
					A gradual scale of 0.5 h walking from residential cells	0–10
					Areas further than 1 h walking distance have been made less attractive	−20
Pasture	For 70 CE and 140 CE the land use from the previous time slice has been reused. A value of 20 had been given	20	A score between 0 and 5 representing the physical suitability ×2	0–10	A gradual scale of 1 h walking from residential cells	0–10
					A gradual scale of 2 h walking from residential cells. This value is a little lower to increase the attractiveness of 1 h walking	0–5

(continued on next page)

Table A3 (*continued*)

Land-use type	Start situation		Physical suitability		Distance relationships	
	Description	Values	Description	Values	Description	Values
					Areas further than 2 h walking distance have been made less attractive	−20
Meadow	See pasture	20	A score between 0 and 5 representing the physical suitability ×2	0–10	A gradual scale of 1 h walking from residential cells. Has been made less attractive to allow pasture to be place nearer to residential cells	0–5
					A gradual scale of 2 h walking from residential cells. This value is a little lower to increase the attractivity of 1 h walking	0–3
					Areas further than 2 h walking distance have been made less attractive	−20
Woodland	Endogenous	–	–	–		
Unused land	All cells from this category has been given a value of −1 ensuring the PLUS will use this category to fill the remaining cells with	−1	–	–	–	–
Infrastructure	Exogenous	–	–	–	–	–

Appendix B. Demand for land-use types

Table B1
Overview of the assumptions to calculate the demand for land use for rural settlements 70 CE and 140 CE foremost based on Van Dinter et al. (2014).

Demand for food (general)

- Settlements were on average inhabited by 10 people (Bloemers, 1978; Willems, 1986; Vos, 2009; Heeren, 2009)
- An adult person would on average need 2200 kCal per day (Van Dinter et al., 2014; Gregg, 1988)
- 67.5% of the food is acquired from arable farming (i.e. cereals) (Kooistra, 1996)
- 22.5% of the food is acquired from animal meat (Kooistra, 1996)
- 10% of the food is derived from other plant-based or animal products, which are on such a small scale that they don't need extra land. These have therefore been left out of the calculations (Kooistra, 1996)

Arable farming (cereals)

- One kilogram of cereals produces 3100 kCal (Kooistra, 1996)
- One hectare produces 1000 kg per year of which 800 kg can be consumed. The other 200 kg are needed for the next sowing season (Van Dinter et al., 2014)
- Half of the required kCal per year will be produced as surplus to survive bad years (Van Dinter et al., 2014)
- After a year of arable farming, the land will be fallow (Van Dinter et al., 2014)

Calculation for the demand of arable farming per rural settlement

- (67.5% (percentage of diet) × 2200 kCal (daily need per person) × 10 (number of persons per settlement) × 365 (number of days per year)) / (800 kg (yearly weight of cereals) × 3100 kCal (amount of kCal per kilo cereals)) × 1.5 (surplus production) × 2 (to take fallow lands into account) = 6.6 ha of arable farming needed per settlement

Pasture and meadow (for meat)

- Every settlement had a herd of approximately 50 animals (cows) which could produce 3,800,000 kCal of meat per year (which they did not have to use) (Van Dinter et al., 2014)
- Every herd needs 16 ha as pasture lands and 10.1 ha meadows (Van Dinter et al., 2014)
- In periods that lands for arable farming are fallow, these are used as pasture (Van Dinter et al., 2014)

Calculation for the demand of pasture per rural settlement

- (22.5% (percentage of diet) × 2200 kCal (daily need per person) × 10 (number of persons per settlement) × 365 (number of days per year)) = 1,806,750 kCal
- 1,806,750 kCal (required production from a herd) / 3,800,000 kCal (maximum production meat of a herd of 50 animals) = 47% of the meat had been used
- 16 (ha needed for pasture for a herd of 50 cows) - 3.3 (fallow land) = 12.7 ha pasture needed per settlement

10.1 ha meadow needed per settlement

Table B2
Overview of the assumptions to calculate the demand for land use for military structures 70 CE and 140 CE foremost based on Van Dinter et al. (2014).

Demand for land
Normal forts accommodated 350 soldiers, larger forts 700 (Glasbergen and Groenman-van Waateringe, 1974; Van Dinter et al., 2014)
An average soldier needs 3000 kCal per day, a *vicus* inhabitant 2200 (Van Dinter et al., 2014; Roth, 1999)
A soldier's diet had the same ratio as a normal person: i.e. 67.5% cereals, 22.5% meat and 10% other resources that do not need significant land (Kooistra, 1996)
A normal *vicus* would have had approximately 350 inhabitants a large *vicus* 700 (Sommer, 1984, 1991; Van Dinter et al., 2014)

For calculating the demand of arable land that is needed to sustain the Roman military in 70 CE and 140 CE the following calculation is applied per sub region:

((a (Number of normal forts) × 350 (number of soldiers) + b (Number of large forts) × 700 (number of soldiers)) × 3000 (kCal per day needed for a soldier) × 365 (days in a year) × 0.675 (% of diet existing of cereal)) + ((c (Number of normal *vici*) × 350 (number of inhabitants) + d (Number of large *vici*) × 700 (number of inhabitants)) × 2200 (kCal per day needed for a normal person) × 365 (days in a year) × 0.675 (% of diet existing of cereal)) / (3100 (kCal per kg) × 800 kg (the useful amount of kilos that 1 ha produces) × 2 (to include fallow lands) = the number of ha of additional arable land required.

For calculating the demand of meat the first step is to calculate the amount of kCal required:

((a (Number of normal forts) × 350 (number of soldiers) + b (Number of large forts) × 700 (number of soldiers)) × 3000 (kCal per day needed for a soldier) × 365 (days in a year) × 22.5 (% of diet existing of meat)) + ((b (Number of normal *vici*) × 350 (number of inhabitants) + d (Number of large *vici*) × 700 (number of inhabitants)) × 2200 (kCal per day needed for a normal person) × 365 (days in a year) × 22.5 (% of diet existing of meat)) = the total kCal of meat required for the Roman army and *vici* inhabitants.

Since every rural settlement is assumed to have had a herd of approximately 50 animals which has the potential of producing 3,800,000 kCal of meat per year of which only 1,806,750 kCal is used, every settlement could at least deliver 1,993,250 kCal without needing additional pasture and meadows. By multiplying this figure with the number of rural settlements and subtract this from the total amount of meat required for the Roman army and *vici* one can calculate the additional kCal still needed, thus calculating how many additional herds are required and what the impact would be on the land-use.

Appendix C. Supplementary data

The software, modelling configuration including a set of scripts to run the model, and modelling results are available at:

http://hdl.handle.net/10411/GO2HVB

Password: HERCULES

Please note, that this is a temporary solution. At the moment that the article would be published we will make it available through a sustainable link in a long term repository (e.g. DANS https://dans.knaw.nl/nl, HERCULES'S Knowledge HUB http://www.hercules-landscapes.eu/knowledge_hub.php or differently when requested by the journal's publishers).

References

Baum, T., 2016. Simulating land use of prehistoric wetland settlements: did excessive resource use necessitate a highly dynamic settlement system? In: Barceló, J.A., Del Castillo, F. (Eds.), Simulating Prehistoric and Ancient Worlds. Springer, pp. 255–280.

Bloemers, J.H.F., 1978. Rijswijk (ZH), De Bult. Eine Siedlung der Cananefaten (PhD thesis University of Amsterdam). Nederlandse Oudheden 8, Amersfoort.

Brinkkemper, O., 1991. Wetland farming in the area to the south of the Meuse estuary during the iron age and Roman period. An environmental and palaeo-economic reconstruction. Analecta Praehistorica Leidensia 24, 226 (this reference is referred to in Appendix A).

Bult, E.J., 1983. Midden-Delfland, een archeologische kartering, inventarisatie, waardering en bewoningsgeschiedenis. In: Nederlandse Archeologische Rapporten (NAR) 2, Amersfoort.

Bürgi, M., Hersperger, A., Schneeberger, N., 2004. Driving forces of landscape change - current and new directions. Landsc. Ecol. 19, 857–868.

Cohen, K.M., Stouthamer, E., Hoek, W.Z., Berendsen, H.J.A., Kempen, H.F.J., 2009. Zand in banen; Zanddieptekaarten van het rivierengebied en het IJsseldal in de provincies Gelderland en Overijssel. 130 Utrecht University Repository.

Danielisová, A., Olševičová, K., Cimler, R., Machálek, T., 2015. Understanding the iron age economy: sustainability of agricultural practices under stable population growth. In: Wurzer, G., Kowarik, K., Reschreiter, H. (Eds.), Agent-based Modeling and Simulation in Archaeology. Springer, Cham, pp. 205–241.

De Cet, M., Duttmann, R., Lull, V., Micó, R., Müller, J., Rihuete Herrado, C., Risch, R., Verhagen, P., 2015. Agricultural territories and GIS modelling: the long-term case study of Menorca. In: Traviglia, A. (Ed.), Across Space and Time. Amsterdam University Press, Amsterdam, pp. 224–238 Papers from the 41st Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA), Perth, 25-28 March 2013.

Deeben, J.H.C., Groenewoudt, B.J., Hallewas, D.P., Van Rooijen, C.A.M., Zoetbrood, P.A.M., 2006. In search of the archaeological resource. In: Berichten van de Rijksdienst voor Oudheidkundig Bodemonderzoek (BROB). 46. pp. 113–126 Amersfoort.

Diogo, V., Koomen, E., Kuhlman, T., 2015. An economic theory-based explanatory model of agricultural land-use patterns: The Netherlands as a case study. Agric. Syst. 139, 1–16.

Glasbergen and Groenman-van Waateringe, 1974. The pre-Flavian garrisons of Valkenburg Z.H.: fabriculae and bipartite barracks, Amsterdam, London. In: Cingula 2.

Goodchild, H., Witcher, R., 2010. Modelling the Agricultural Landscapes of Republican Italy. In: Carlsen, J., Lo Cascio, E. (Eds.), Agricoltura e Scambi nellItalia tardo repubblicana, Bari: Edipuglia, pp. 187–220.

Gregg, S.A., 1988. Foragers and Farmers: Population, Interaction and Agricultural Expansion in Prehistoric Europe. University of Chicago Press, Chicago.

Groenhuijzen, M.R., Verhagen, P., 2015. Exploring the dynamics of transport in the Dutch limes. eTopoi J. Anc. Stud. Special Vol. 4, 25–47.

Groenhuijzen, M.R., Verhagen, P., 2017. Comparing network construction techniques in the context of local transport networks in the Dutch part of the Roman limes. J. Archaeol. Sci. Rep. 15, 235–251. https://doi.org/10.1016/j.jasrep.2017.07.024.

Groot, M., Heeren, S., Kooistra, L.I., Vos, W.K., 2009. Surplus production for the market? The agrarian economy in the non-villa landscapes of Lower Germany. J. Roman Archaeol. XX, 231–252.

Heeren, S., 2009. Romanisering van rurale gemeenschappen in de civitas Batavorum. In: De casus Tiel-Passewaaij. Free University Amsterdam, Amsterdam (PhD Thesis).

Higgs, E.S., Vita-Finzi, C., 1972. Prehistoric economy: a territorial approach. In: Higgs, E.S. (Ed.), Papers in Economic Prehistory: Studies by Members and Associates of the British Academy Major Research Project in the Early History of Agriculture. Cambridge University Press, Cambridge, pp. 27–36.

Hilferink, M., Rietveld, P., 1999. Land use scanner: an integrated GIS-based model for long term projections of land use in urban and rural areas. J. Geogr. Syst. 1 (2), 155–177.

Hughes, R.E., Weiberg, E., Bonnier, A., Finné, M., Kaplan, J.O., 2018. Quantifying land use in past societies from cultural practice and archaeological data. Land 7 (1), 9. http://dx.doi.org/10.3390/land7010009.
Joyce, J., Verhagen, P., 2016. Simulating the farm: computational modelling of cattle and sheep herd dynamics for the analysis of past animal husbandry practices. In: XXX, XXX, Proceeding Landscape Archaeology Conference 2014; The Wind of Change: Town, Country, Land-Use and Settlement Patterns Between the fourth and the Seventh Century AD, Berlin, http://dx.doi.org/10.5463/lac.2014.59.
Kohler, T.A., 2000. Putting social sciences together again: An introduction to the volume. In: Kohler, T.A., Gumerman, G.J. (Eds.), Dynamics in Human and Primate Societies: Agent-Based Modelling of Social and Spatial Processes. Oxford University Press, New York, pp. 1–44.
Kohler, T.A., Varien, M.D., 2012. Emergence and collapse of early villages in the central Mesa Verde: An introduction. In: Emergence and Collapse of Early Villages in the Central Mesa Verde: Models of Central Mesa Verde Archaeology. University of California Press, Berkeley, pp. 1–14.
Kohler, T.A., Johnson, D., Varien, M., Ortman, S., Reynolds, R., Kobti, Z., Cowan, J., Kolm, K., Smith, S., Yap, L., 2007. Settlement ecodynamics in the prehispanic central Mesa Verde region. In: Kohler, T.A., Van der Leeuw, S. (Eds.), The Model-Based Archaeology of Socionatural Systems. SAR Press, Santa Fe, pp. 61–104.
Kooistra, L., 1996. Borderland Farming. Possibilities and Limitations of Farming in the Roman Period and Early Middle Ages between the Rhone and Meuse. (Assen/PhD thesis Leiden University).
Kooistra, L., Van Dinter, M., Dütting, M.K., Van Rijn, P., Cavallo, C., 2013. Could the local population of the lower Rhine Delta supply the Roman Army? Part 1: the archaeological and historical framework. J. Archaeol. Low Ctries. 4, 5–50.
Land-use modelling in planning practice. In: Koomen, E., Borsboom-Van Beurden, J. (Eds.), GeoJournal Library. 101 Springer, Dordrecht.
Koomen, E., Hilferink, M., Borsboom-Van Beurden, J., 2011. Introduction land use scanner. Chapter 1. In: Koomen, E., Borsboom-van Beurden, J. (Eds.), Land-Use Modelling in Planning Practice. GeoJournal Library. 101 Springer, Dordrecht.
Koomen, E., Diogo, V., Dekkers, J.E.C., Rietveld, P., 2015. A utility-based suitability framework for integrated local-scale land-use modeling. Comput. Environ. Urban. Syst. 50, 1–14. http://dx.doi.org/10.1016/j.compenvurbsys.2014.10.002.
Lake, M., 2014. Trends in archaeological simulation. J. Archaeol. Method Theory 21, 258–287.
Lavalle, C., Baranzelli, C., Batista e Silva, F., Mubareka, S., Rocha Gomes, C., Koomen, E., Hilferink, M., 2011. A high resolution Land use/cover modelling framework for Europe: introducing the EU-ClueScanner100 model. In: Murgante, B., Gervasi, O., Iglesias, A., Taniar, D., Apduhan, B.O. (Eds.), Computational Science and Its Applications - ICCSA 2011, Part I, Lecture Notes in Computer Science. 6782. Springer-Verlag, Berlin, pp. 60–75.
Loonen, W., Koomen, E., 2009. Calibration and validation of the Land Use Scanner allocation algorithms. In: PBL Publication Number 550026002. Netherlands Environmental Assessment Agency (PBL), Bilthoven.
Mc Fadden, D., 1978. Modelling the choice of residential location. In: Karlsqvist, A., Lundqvist, L., Snickars, F., Weibull, J. (Eds.), Spatial Interaction Theory and Planning. North Holland Publishers, Amsterdam, pp. 75–96.
Polak, M., 2009. The Roman military presence in the Rhine Delta in the Period c. AD 40–140. In: Morillo, A., Hanel, N., Martín, E. (Eds.), LIMES XX. Roman Frontier Studies 13. Madrid, pp. 945–953.
Robb, J., Van Hove, D., 2003. Gardening, foraging and herding: neolithic land use and social territories in southern Italy. Antiquity 77, 241–254.
Roorda, I.M., Wiemer, R., 1992. The ARCHIS project: towards a new national archaeological record in the Netherlands. In: Larsen, C. (Ed.), Sites and Monuments: National Archaeological Records. The National Museum of Denmark, Copenhagen, pp. 117–122.
Roth, J.P., 1999. The logistics of the Roman army at war: (264 B.C.–A.D. 235). In: Colombia Studies in the Classical Tradition. 23 Leiden Boston Köhln.
Sommer, C.S., 1984. The military vici in Roman Britain aspects of their origins, their location and layout, administration, function and end. In: BAR Int. Series 129 Oxford.
Sommer, C.S., 1991. Life beyond the ditches: housing and planning of the military vici in Upper Germany and Raetia. In: Maxfield, V.A., Dobson, M.J. (Eds.), Roman frontier studies 1989, Proceedings of the XVth International Congress of Roman Frontier Studies, Exeter, pp. 472–476.
Van der Leeuw, S.E., McGlade, J. (Eds.), 1997. Time, Process and Structured Transformation in Archaeology. Routledge, London.
Van Dinter, M., Kooistra, L.I., Dütting, M.K., Van Rijn, P., Cavallo, C., 2014. Could the local population of the lower Rhine Delta supply the Roman Army? Part 2: modelling the carrying capacity using archaeological, Palaeo-ecological and geomorphological data. J. Archaeol. Low Countries (JALC) 5, 5–50.
Van Es, W.A., 1981. De Romeinen in Nederland, Bussum.
Van Lanen, R.J., Kosian, M., Groenewoudt, B.J., Spek, Th., Jansma, E., 2015. Best travel options: modelling Roman and early-medieval routes in the Netherlands using a multi-proxy approach. J. Archaeol. Sci. Rep. 3, 144–159.
Van Lanen, R.J., Jansma, E., Van Doesburg, J., Groenewoudt, B., 2016. Roman and early-medieva long-distance transport routes in north-western Europe: modelling frequent-travel zones using a dendrochronological approach. J. Archaeol. Sci. 73, 120–137.
Van Lanen, R.J., De Kleijn, M., Gouw-Bouman, M., Pierik, H.J. (in prep). Exploring Roman and Early-Medieval Habitation of the Rhine-Meuse Delta: Modelling Large-Scale Demographic Changes and Corresponding Land-Use Impact.
Verhagen, P., Gili, S., Micó, R., Risch, R., 1999. Modelling prehistoric land use distribution in the Rio Aguas valley (province of Almería, S.E. Spain). In: Dingwall, L., Exon, S., Gaffney, V., Lafflin, S., Van Leusen, M. (Eds.), Archaeology in the Age of the Internet – CAA97. Computer Applications and Quantitative Methods in Archaeology 25th Anniversary Conference, University of Birmingham. British Archaeological Reports, International Series 750 Archaeopress, Oxford.
Von Thünen, J.H., 1842. Der Isolierte Staat in Beziehung auf Landwirtschaft und Nationalökonomie. Neudruk nach der Ausgabe ketzter Hand. Gustac Fisher Verlag, Stuttgart, Germany.
Vos, W.K., 2009. Bataafs platteland. Het Romeinse nederzettingslandschap in het Nederlandse Kromme- Rijngebied (PhD thesis Vrije Universiteit Amsterdam). 35 Nederlandse Archeologische Rapporten (NAR), Amsterdam/Amersfoort.
Vos, P., De Vries, S., 2013. 2e generatie palaeogeografische kaarten van Nederland (versie 2.0). Deltares, Utrecht Availabel at. www.archeologieinnederland.nl.
Whitley, T.G., Moore, G., Goel, G., Jackson, D., 2010. Beyond the Marsh: settlement choice, perception and spatial decision-making on the Georgia Coastal Plain. In: Frischer, B., Crawford, J., Kollers, D. (Eds.), Making History Interactive. Computer Applications and Quantitative Methods in Archaeology. Proceedings of the 37th Conference, Williamsburg, VA, USA, Oxford. Archaeopress, pp. 380–390.
Wiemer, R., 2002. Standardisation: the key to archaeological data quality. In: García Sanjuan, L., Wheatley, D.W. (Eds.), Mapping the Future of the Past, Managing the Spatial Dimension of the European Archaeological resource, Sevilla, pp. 103–108.
Willems, W.J.H., 1986. Romans and Batavians. In: A Regional Study in the Dutch Eastern River Area. University of Amsterdam, Amsterdam (PhD thesis).
Zandstra, M.J.M., Polak, M., 2012. De Romeinse versterking in Vechten-Fectio. Het archeologisch onderzoek in 1946–1947, Auxiliaria. Nijmegen, Auxilia, pp. 11.